ACCEP
Communication and Computer Engineering Program

BENHA UNIVERSITY
FACULTY OF ENGINEERING (SHOUBRA)
ELECTRONICS AND COMMUNICATIONS ENGINEERING

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FACULTY OF ENGINEERING AT SHOUBRA

CCE 201
Solid State Electronic Devices
(2022 - 2023) term 231

Lecture 4: Current Flow in Semiconductors.

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Outlines

- Drift Current.
- Diffusion Current.
- Summary.

Drift Current:

- Q: What happens when an electrical field (E) is applied to a semiconductor crystal ?

A: When an electric field is applied, the carriers are accelerated by the force due to the electric field (Newton's law). Holes are accelerated in the direction of E, free electrons are repelled.

- How is the velocity of these holes defined?

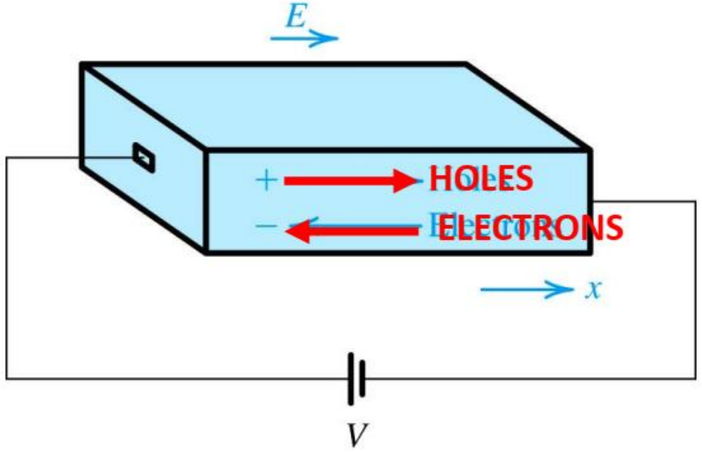
$$\overbrace{v_{p-drift} = \mu_p E}^{\mu_p = \text{hole mobility} \quad E = \text{electric field}} \qquad \overbrace{v_{n-drift} = -\mu_n E}^{\mu_n = \text{electron mobility} \quad E = \text{electric field}}$$

Note: that electrons move with velocity **2.5 times higher** than holes

μ_p (cm^2/Vs) = 480 for silicon

μ_n (cm^2/Vs) = 1350 for silicon

- An electric field E established in a bar of silicon causes the holes to drift in the direction of E and the free electrons to drift in the opposite direction. Both the hole and electron drift currents are in the direction of E.



Drift Current:

- The net drift motion of the ensemble of carriers produces an electric current.
- Electric current density J_{drift} , by definition, is the net charge crossing per unit area of an arbitrary plane per unit time.

$$\boxed{J_p = qpv_{p,drift} = qp\mu_p E}$$

- A similar expression for the electric current due to electrons may be derived.

$$\boxed{J_n = qnv_{n,drift} = (-q)n(-\mu_n E) = qn\mu_n E}$$

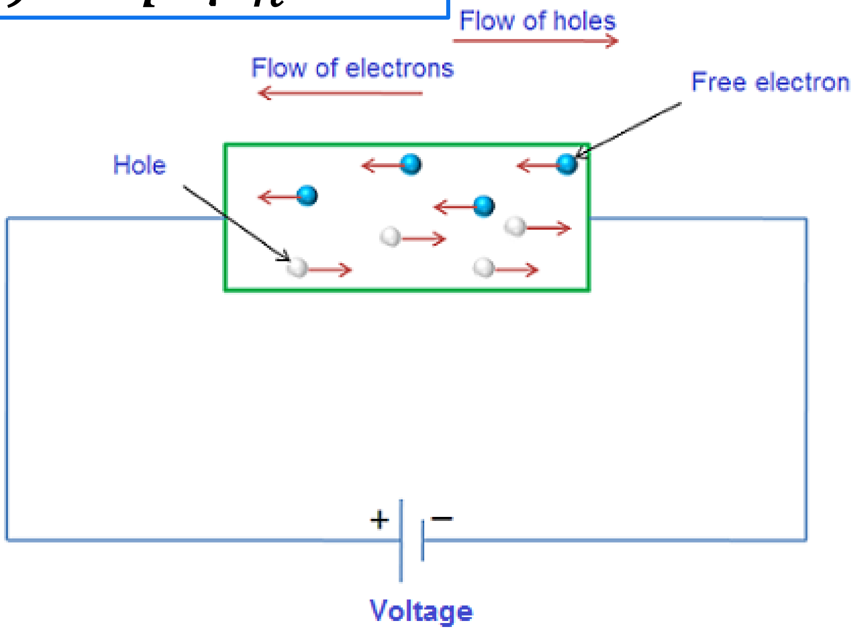
- Electric current:

$$\boxed{I_p = AJ_p = Aqp\mu_p E}$$

$$\boxed{I_n = AJ_n = Aqn\mu_n E}$$

- The total drift current density defined as:

$$\boxed{\begin{aligned} J_{drift} &= J_p + J_n = qp\mu_p E + qn\mu_n E \\ &= q\,(p\mu_p + n\mu_n)\,E = \sigma E \end{aligned}}$$



Drift Current:

- conductivity (σ) : relates current density (J) and electrical field (E)

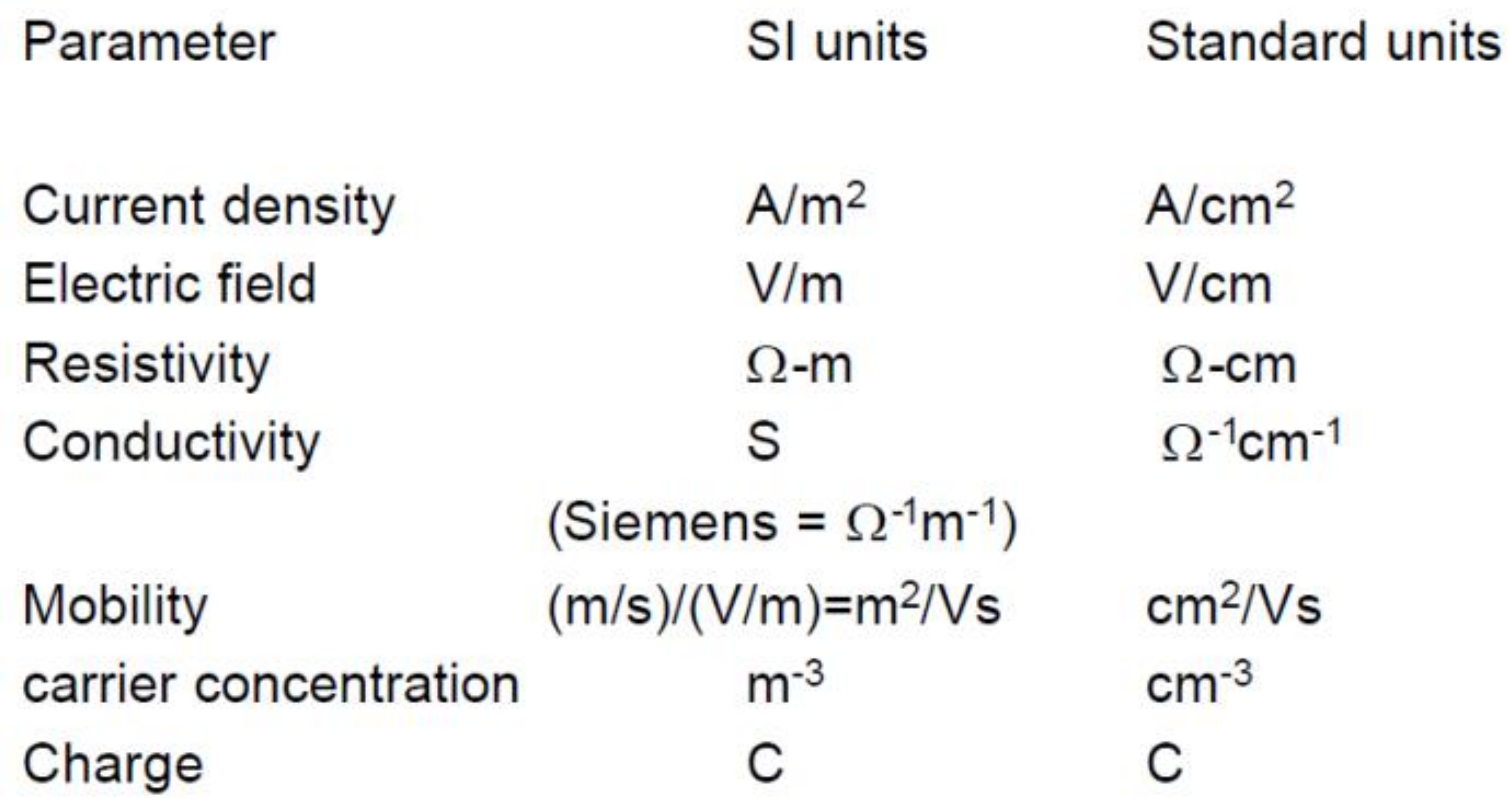
$$\boxed{J = \sigma E}$$

$$\sigma = q\,(\,p\mu_p + n\mu_n)$$

- resistivity (ρ) : relates current density (J) and electrical field (E).

$$\rho = \frac{1}{q\,(\,p\mu_p + n\mu_n)}$$

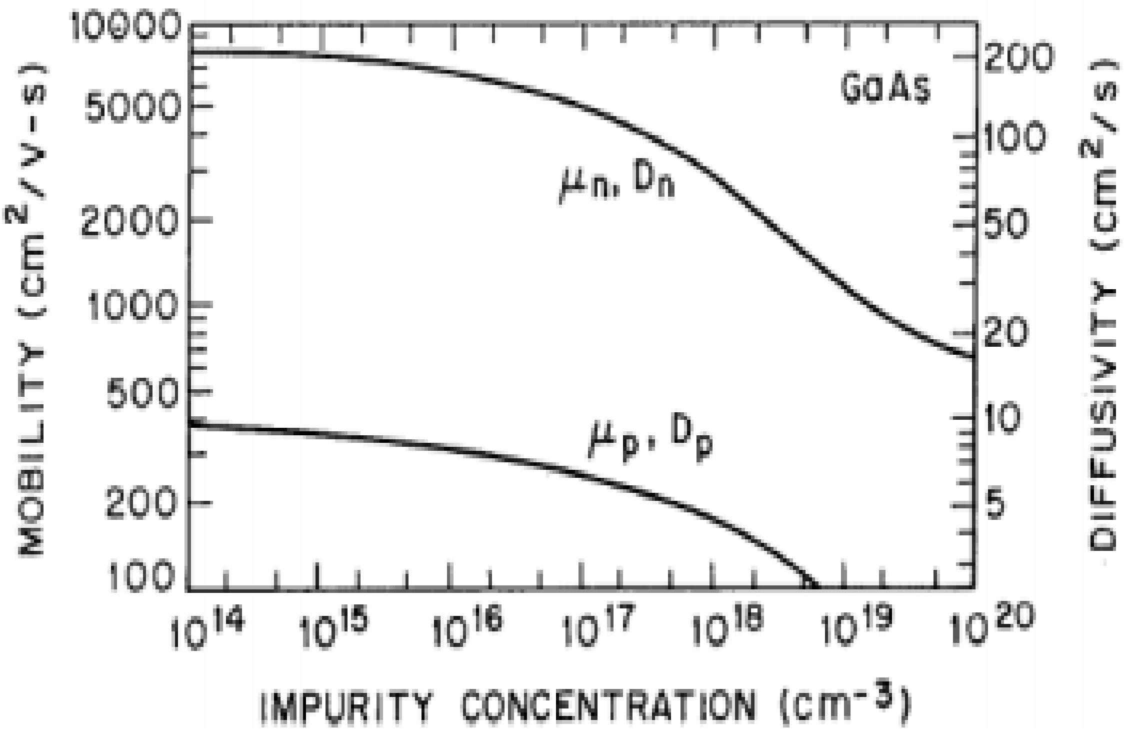
Drift Current:



Parameter	SI units	Standard units
Current density	A/m^2	A/cm^2
Electric field	V/m	V/cm
Resistivity	Ω-m	Ω-cm
Conductivity	S (Siemens = $\Omega^{-1}m^{-1}$)	$\Omega^{-1}cm^{-1}$
Mobility	(m/s)/(V/m)=m^2/Vs	cm^2/Vs
carrier concentration	m^{-3}	cm^{-3}
Charge	C	C

Doping dependence of mobility

Doping reduces carrier mobility



Drift Current:

Q(a): Find the resistivity of intrinsic silicon using following values – $\mu_n = 1350\,cm^2/Vs$, $\mu_p = 480\,cm^2/Vs$, $n_i = 1.5\mathbf{x}10^{10}/cm^3$.

(a) For intrinsic silicon, $p = n = n_i = 1.5 \times 10^{10}/\mathrm{cm}^3$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)} = \frac{1}{1.6\times10^{-19}(1.5\times10^{10}\times480+1.5\times10^{10}\times1350)}$$

$$= 2.28\times10^5\ \Omega.\mathrm{cm}$$

Q(b): Find the resistivity of p-type silicon with $N_A = 10^{16}/cm^2$ and using the following values – $\mu_n = 1110\,cm^2/Vs$, $\mu_p = 400\,cm^2/Vs$, $n_i = 1.5\mathbf{x}10^{10}/cm^3$

(b) For the p-type silicon $p_p \simeq N_A = 10^{16}/\mathrm{cm}^3$

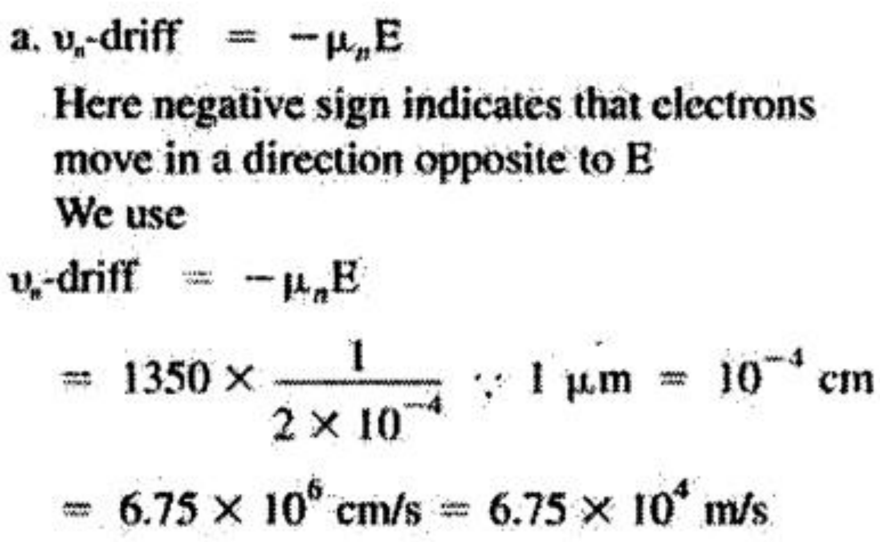
$$n_p \simeq \frac{n_i^2}{N_A} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^4/\mathrm{cm}^3$$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)} = \frac{1}{1.6\times10^{-19}(10^{16}\times400+2.25\times10^4\times1110)}$$

$$= 1.56\,\Omega.\mathrm{cm}$$

Drift Current:

A uniform bar of *n*-type silicon of 2 μm length has a voltage of 1 V applied across it. If $N_D = 10^6/\text{cm}^3$ and $\mu_n = 1350\text{cm}^2/\text{V.s}$, find (a) the electron drift velocity, (b) the time it takes an electron to cross the 2-μm length, (c) the drift-current density, and (d) the drift current in the case the silicon bar has a cross sectional area of $0.25\mu\text{m}^2$.



a. υ_n-driff $= -\mu_n E$

Here negative sign indicates that electrons move in a direction opposite to E

We use

υ_n-driff $= -\mu_n E$

$$= 1350 \times \frac{1}{2 \times 10^{-4}} \quad \because 1\ \mu\text{m} = 10^{-4}\ \text{cm}$$

$$= 6.75 \times 10^6\ \text{cm/s} = 6.75 \times 10^4\ \text{m/s}$$

b. Time taken to cross 2μm length

$$= \frac{distance}{v_{drift}} = \frac{2 \times 10^{-6}}{6.75 \times 10^4} = 30\text{ps}$$

c. The current density J_n is given by

$$J_n = qn\mu_n E$$

$$= 1.6 \times 10^{-19} \times 10^{16} \times 1350 \times \frac{1}{2 \times 10^{-4}} = 1.08 \times 10^4\ \text{A/cm}^2$$

d. Drift current $I_n = J_n A$

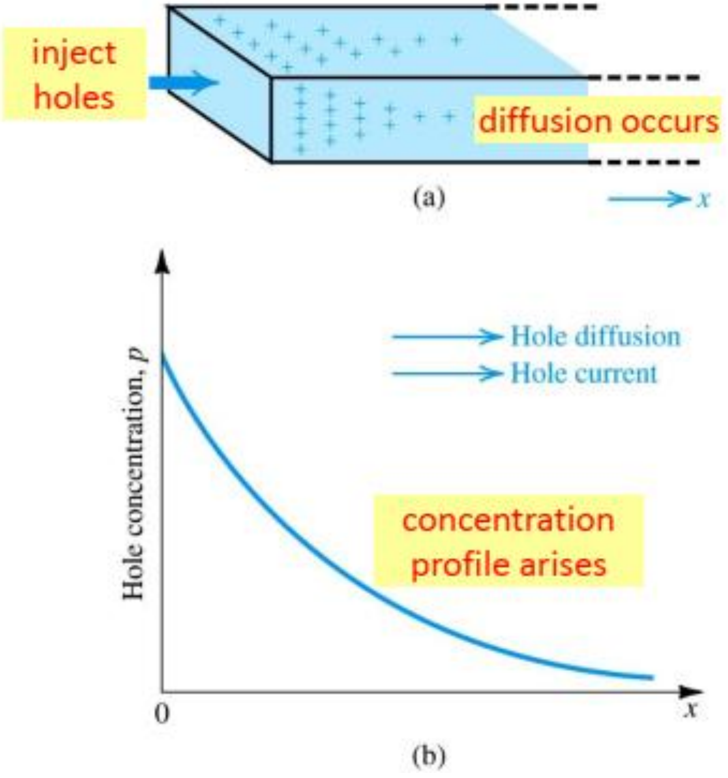
$$I_n = 0.25 \times 10^{-8} \times 1.08 \times 10^4 = 27\mu\text{A}$$

Outlines

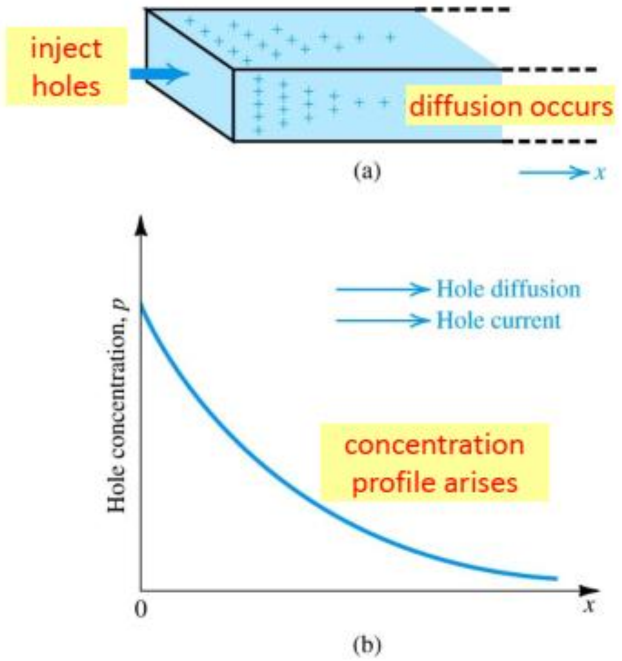
- Drift Current.
- Diffusion Current.
- Summary.

Diffusion Current

- There is another type of current in semiconductors that arises due to the diffusion of carriers. Diffusion is also a consequence of random thermal motion of carriers. But the exact source of diffusion is the non-uniform spatial distribution of carriers.
- We have assumed so far that the carrier concentration distribution is uniform everywhere inside the semiconductor. This may not always be true. For example, the impurity distribution inside a semiconductor may vary due to processing conditions.
- Let us now analyze the consequence of non-uniform distribution of carriers.
- However, when carrier concentration is non-uniform, more number of carriers move out of the higher carrier concentration region than the number of carriers that move into it. As a result, there is a net motion of carriers from **the higher concentration region to a lower concentration region**. Thermal agitation causes the carriers to spread in such a way as to equalize the distribution. This motion of carriers is known as the **diffusion**.



Diffusion Current



J_p = current flow density attributed to holes

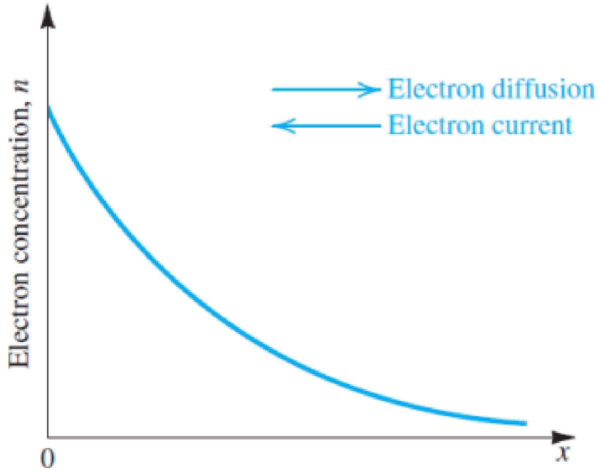
q = magnitude of the electron charge

D_p = diffusion constant of holes ($12 \text{cm}^2/\text{s}$ for silicon)

$\mathbf{p}(x)$ = hole concentration at point x

$d\mathbf{p}/dx$ = gradient of hole concentration

hole diffusion current density : $J_p = -qD_p \dfrac{d\mathbf{p}(x)}{dx}$



electron diffusion current density : $J_n = +qD_n \dfrac{d\mathbf{n}(x)}{dx}$

J_n = current flow density attributed to free electrons

D_n = diffusion constant of electrons ($35 \text{cm}^2/\text{s}$ for silicon)

$\mathbf{n}(x)$ = free electron concentration at point x

$d\mathbf{n}/dx$ = gradient of free electron concentration

Observe that a negative (dn/dx) gives rise to a negative current, a result of the convention that the positive direction of current is taken to be that of the flow of positive charge (and opposite to that of the flow of negative charge).

Diffusion Current

Consider a bar of silicon in which a hole concentration **p**(x) described below is established.

Q(a): Find the hole-current density J_p at $x = 0$.

Q(b): Find current I_p.

- Note the following parameters: $p_0 = 10^{16}/cm^3$, $L_p = 1\mu m$, $A = 100\mu m^2$

$$\mathbf{p}(x) = p_0 e^{-x/L_p}$$

$$J_p = -qD_p \frac{dp(x)}{dx} = -qD_p \frac{d}{dx}\left[p_o e^{-x/L_p}\right]$$

$$J_p(0) = q\frac{D_p}{L_p}p_0 = 192\ \text{A/cm}^2$$

$$I_p = J_p \times A = 192\ \mu\text{A}$$

Relationship Between D and μ

- the relationship between diffusion constant (D) and mobility (μ) is defined by thermal voltage (v_T).
- known as **Einstein Relationship:** $$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$
- Thermal voltage: $$V_T = \frac{KT}{q}$$ at T = 300K, VT = 25.9mV

Summary :

$$J_{p,drift} = qp\mu_p E$$

$$I_p = Aqp\mu_p E$$

$$J_{n,drift} = qn\mu_n E$$

$$I_n = Aqn\mu_n E$$

$$J_{drift} = J_{p,drift} + J_{n,drift} = q\,(p\mu_p + n\mu_n)\,E = \sigma E$$

$$J_{p,diff} = -qD_p \frac{dp(x)}{dx}$$

$$I_p = -AqD_p \frac{dp(x)}{dx}$$

$$J_{n,diff} = qD_n \frac{dn(x)}{dx}$$

$$I_n = AqD_n \frac{dn(x)}{dx}$$

$$J_{diff} = J_{p,diff} + J_{n,diff} = -qD_p \frac{dp(x)}{dx} + qD_n \frac{dn(x)}{dx}$$

$$E = \frac{v}{l}$$

$$\sigma = q\,(p\mu_p + n\mu_n)$$

$$\rho = \frac{1}{q\,(p\mu_p + n\mu_n)}$$

$$\frac{\boldsymbol{D_n}}{\boldsymbol{\mu_n}} = \frac{\boldsymbol{D_p}}{\boldsymbol{\mu_p}} = \boldsymbol{V_T}$$

$$\boldsymbol{V_T} = \frac{\boldsymbol{KT}}{\boldsymbol{q}}$$

$$J_{Total} = J_{drift} + J_{diff} = \left[\boldsymbol{q\,(p\mu_p + n\mu_n)\,E}\right] + \left[\boldsymbol{-qD_p \frac{dp(x)}{dx} + qD_n \frac{dn(x)}{dx}}\right]$$

END OF LECTURE

BEST WISHES